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Novel Cyclic Prefix Selection to Improve Spectral Efficiency and Signal Strength in OFDM Systems

Budhaditya Bhattacharyya[1], Iti Saha Misra[2] and Salil Kumar Sanyal[2]
[1]School of Mobile Computing and Communication, Jadavpur University, Kolkata, India
bhattacharyya.budhaditya@gmail.com
[2]Department of Electronics and Telecommunication Engineering, Jadavpur University, Kolkata, India
itisahamisra@yahoo.co.in, s_sanyal@ieee.org

Abstract— **The primary objective of using a guard interval in form of Cyclic Prefix (CP) for WiMAX has always been to mitigate the adverse effect of Inter Symbol Interference (ISI) due to multipath fading. However, recent researches on Adaptive Cyclic Prefix (ACP) have been suggested instead of the existing fixed CP duration for changing Channel SNR. These strategies provide a better Quality of Service (QoS) and also enhances the performance of OFDM based WiMAX systems. Based on these strategies, an "error on the fly" correction based ACP has been proposed in this paper. The proposed method, accompanied by exhaustive simulation results, show its effectiveness by the improved Spectral Efficiency (SE) and better Signal strength for a typical WiMAX scenario under fast fading multipath channel conditions.**

Keywords-**Data Rate; Spectral Efficiency; Adaptive Cyclic Prefix**

I. Introduction

IEEE 802.16e Mobile WiMAX (World Interoperability for Microwave Access) was an extension to the existing standards of IEEE 802.16d or 802.16-REVd, to support mobility of user or subscribers [1-2]. Although promising a theoretical data rate of 70 Mb/s for a range of up to a maximum of 50 km [3], for practical scenario only 15 Mbps can only be obtained for a region with 3 Km cell radius and vehicular speeds greater than 100 Km/h without the need of direct Line-Of-Sight (LOS) [4]. However, even these throughputs suffer heavily due to different propagation loss associated with signal transmission through multipath fading channels.

Different strategies in form of Orthogonal Frequency Division Multiplexing (OFDM) and Multiple Input Multiple Output (MIMO) OFDMA techniques have also been applied to maintain a substantially high data rate without compromising Quality of Services (QoS). Along with it, strategies in form of Adaptive Modulation and Coding (AMC) [5] have been categorically used to improve QoS at severely poor channel scenario.

Effective synchronization error causes severe SNR degradation [6-7]. Even [8-9] have also provided solutions to SNR improvement, by effective use of Cyclic Prefix (CP) in a WiMAX scenario. On one hand judicious selection of CP mitigates ISI and ICI between subcarriers, while on the other it improves the transmitted signal strength. However, using a fixed guard interval throughout the entire duration of operation makes the design overhead to rise while significant improvement of signal strength have been compromised. Arguably, using a longer guard interval reduces the opportunity of transmitting valid data subcarriers instead of redundant guard subcarriers. On that same note [10-11] have already proposed that an adaptive adjustment of CP or Adaptive Cyclic Prefix (ACP), has a better control over the parameters like Power loss, Mean Square Error (MSE).

Improvement of both average error performance and significantly enhanced data rate are the crucial importance of ACP. Raw Data Rate (RDR) has significant influence on Spectral Efficiency (SE) of the system. Thus a high data rate will guarantee a much improved spectrally efficient system. Through the simulation results presented in this paper the crucial contribution of unique "error on fly correction" based dynamic selection of CP has been confirmed. Hence this novel technique contributes in forming the two primary objective of this paper, which are,

1. To significantly improve transmitted signal strength by effective CP selection.
2. Moreover, an enhanced spectral efficient OFDM based WiMAX network under Rayleigh Fading Channels is presented beforehand.

II. Background

A. Relation between Raw Data Rate, Spectral Efficiency and SNR improvement with reference to WiMAX

OFDM has always been a spectrally efficient multiplexing technique that is fundamental efficient WiMAX design. Keeping subcarriers orthogonal to each other (non-overlapping in nature), an increased number of data subcarriers can be accommodated within a specified Bandwidth (BW). Hence in one hand data rate improves resulting in a spectrally efficient system. However, in practice due to the pertinent loss associated with different fading channels, necessities the use of CP as guard interval. The data redundancy brought about by CP minimizes the adverse effect of Inter Symbol Interference (ISI) and Inter Carrier Interference (ICI) within useful OFDM symbol duration. Hence calculation of RDR for WiMAX is very crucial from the context of application of CP.

The analytical expression for RDR as presented in [4] does not take into account coding rate. Instead it considers the raw "modulated" complex data. However, before transmission, these complex data sets must be encoded to reduce bit error probability. Hence in support to these arguments, [12-14] suggest that modulation scheme (B_s), code rate (C_d), number of used data subcarriers (N_{sub}) and overall symbol duration (T_{symbol}) affects data rate at significant

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proportions as described in (1).

$$RDR = \frac{(N_{sub} \times B_s \times C_d)}{T_{symbol}} \quad (1)$$

It is indeed evident that using a higher order modulation and code rate a high RDR can be guaranteed provided T_{symbol} is small. N_{sub}, Bs , C_d are considered as per the WiMAX standards specified in Table. I and Table. II, while T_{symbol} is calculated as per (2).

TABLE I. PARAMETER SPECIFICATIONS

Parameters	Value
Bandwidth (BW)	Variable from 1.25 to 20 MHz, must vary as an integral multiple of 1.25, 1.5 or 1.75
Number of Subcarriers (N_{sub})	128, **256**, 512, 1024, 2048
Sampling Ratio (n_f)	1. For BW: multiple of 1.75 MHz n_f = 8/7, 2. For BW: multiple of 1.5 MHz n_f = 86/75 3. For BW: multiple of 1.25 MHz n_f = 144/125 4. For BW: multiple of 2.75 MHz n_f = 316/275 **5. For BW: multiple of 2.0 MHz n_f = 57/50** 6. For BW not otherwise specified, n_f = 57/50
FFT Size	128,256, 512, 1024, 2048
Cyclic Prefix (CP)	¼ , 1/8, 1/16, 1/32
Modulation Schemes and Code Rate	BPSK (1/2), QPSK(1/2), QPSK(3/4), 16-QAM(1/2), 16-QAM(3/4), 64-QAM(2/3), 64-QAM(3/4)

TABLE II. SPECIFICATION OF DATA SUBCARRIERS AS OFDM AND OFDMA S TANDARDS [9]

Parameter	OFDM	OFDMA			
FFT Size(N_{FFT})	**256**	128	512	1024	2048
Data Subcarriers	**192**	72	360	720	1440
Pilot Subcarriers	**8**	12	60	120	240
Guard / Null Subcarriers	**56**	44	92	184	368

Several earlier discussions as [9], [14] have already deduced that the sum of useful symbol time (T_u) and CP time (T_{cp}) produces T_{symbol}, where T_u and T_{cp} can be defined as (2)

$$T_u = \frac{1}{\Delta f_{spacing}}; \quad \text{and} \quad T_{cp} = CP \times T_u \quad (2)$$

Now frequency spacing ("$f_{spacing}$) can be defined as (3)

$$\Delta f_{spacing} = \frac{F_{sampfreq}}{N_{FFT}}; \text{and } F_{sampfreq} = \left\lfloor \frac{n_f \times BW}{8000} \right\rfloor \times 8000 \quad (3)$$

Instead of considering $F_{sampfreq}$ as only the product of n_f and BW mentioned in [13-14], a more standardized approach as in [4],[15] have been considered in this paper. So (2) can be rewritten as (4)

$$T_u = \frac{N_{FFT}}{\left\lfloor \frac{n_f \times BW}{8000} \right\rfloor \times 8000} \quad \text{and} \quad T_{cp} = \frac{CP \times N_{FFT}}{\left\lfloor \frac{n_f \times BW}{8000} \right\rfloor \times 8000} \quad (4)$$

Hence CP plays a pivotal role in calculating T_{symbol}. For a specified BW of 10 MHz the overall simulation has been done while considering n_f as 57/50 following Table. I. Based on the aforementioned condition SE and RDR has been calculated for all possible modulation and coding standards as mentioned in Table. III. SE can be defined as a normalized quantity that depends on bits per second or RDR per Hz of channel BW [13-14]. Alternatively the ratio of channel capacity to BW gives Bandwidth Efficiency compared to SE [4]. Hence judicious selection of CP guarantees a better SE and RDR. On the same note it can also be mentioned that CP has influential role in controlling SNR_{loss} for WiMAX as reported in [4], [8-9]. Using the general expression of (5) it can easily be deduced that a smaller CP (like CP=1/32) provides a better performance by preventing major drop in signal strength. So the above discussions confirm that a smaller CP guarantees a better signal strength, a much improved RDR and also an efficient SE for a OFDM system. Hence using existing Modified Adaptive Cyclic Prefix (MACP) algorithm [15] the Average Synchronization Error (ASE) is reduced while ESA provides a unique strategy to maintain a smaller CP at all possible Channel SNR.

$$SNR_{loss} = -10 \log\left(\frac{1}{1+CP}\right) \quad (5)$$

III. ERROR SYNCHRONIZATION ALGORITHM

A. Roadmap to selection algorithm

Synchronization error detection and correction, based on Channel SNR is one among many other algorithms primarily related to improving the error performance using adaptive use of CP [11] [16-17]. However, these algorithms fail to calculate and correct synchronization "error on the fly". By the term "on the fly" it is implied that instead of varying CP for a specific "range" of Channel SNR, guard interval must be varied for each changing Channel SNR [11].

Like in ACP strategy, Channel SNR was sub divided into four categories. Channel SNR ranging between 1 dB to 20 dB, were subdivided into 1-5 dB (P), 6-10 dB (Q), 11-15 dB (R) and 16-20 dB (S) respectively [11]. Now for particular ASE thresholds like A, B, C and D there exists three possibilities like,

1. There are scenarios wherein Average Synchronization Error (ASE) is low under low Channel SNR condition.
2. There are instances when ASE is low under favorable Channel SNR condition.
3. A high ASE, given a low Channel SNR or a high ASE under good Channel SNR condition.

Based on these assumptions a one–to-one mapping has been established between all possible combinations of ASE with respect to predicted CP over changing Channel SNR as depicted in Fig. 1. Like shown in Fig. 2, each ASE threshold (like A, B, C or D) must belong to one of the Channel SNR ranges (P, Q, R or S) following the above four conditions. Accordingly, for each ASE threshold, a particular CP is selected in increasing order of redundancy (G1=1/32, G2=1/16, G3=1/8 and G4=1/4). So for each and every varying channel condition CP gets dynamically changed if and only if ASE falls below certain threshold (like from ASE threshold A to B) as depicted in Fig. 1. The proposed Error Synchronization Algorithm (ESA) is primarily a modification of ACP and MACP algorithms as described in [11] and [16].

By ESA it can be concluded that instead of mandatory hopping from CP = ¼ to CP = 1/8 for changing Channel SNR ranges, a dynamic change of CP *only* occurs when

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TABLE III. RAW DATA RATE AND SPECTRUM EFFICIENCY FOR ALL POSSIBLE MODULATION AND CODING STANDARDS AS PER WIMAX

Modulation Type	Coding Rate	Cyclic Prefix=1/4		Cyclic Prefix=1/8		Cyclic Prefix=1/16		Cyclic Prefix=1/32	
		Raw data rate (Mbps)	Spectrum Efficiency	Raw data rate (Mbps)	Spectrum Efficiency	Raw data rate (Mbps)	Spectrum Efficiency	Raw data rate (Mbps)	Spectrum Efficiency
BPSK	1/2	3.4176	0.3418	3.80	0.3797	4.0207	0.4021	4.1425	0.4143
QPSK	1/2	6.8352	0.6835	7.5947	0.7595	8.0414	0.8041	8.2851	0.8285
QPSK	3/4	10.2528	1.0253	11.392	1.1392	12.0621	1.2062	12.4276	1.2428
16-QAM	1/2	13.6704	1.367	15.200	1.5189	16.100	1.6083	16.5702	1.657
16-QAM	3/4	20.5056	2.0506	22.800	2.2784	24.100	2.4124	24.900	2.4855
64-QAM	2/3	27.3408	2.7341	30.3787	3.0379	32.200	3.2166	33.100	3.314
64-QAM	3/4	30.7584	3.0758	34.200	3.4176	36.200	3.6186	37.300	3.7283

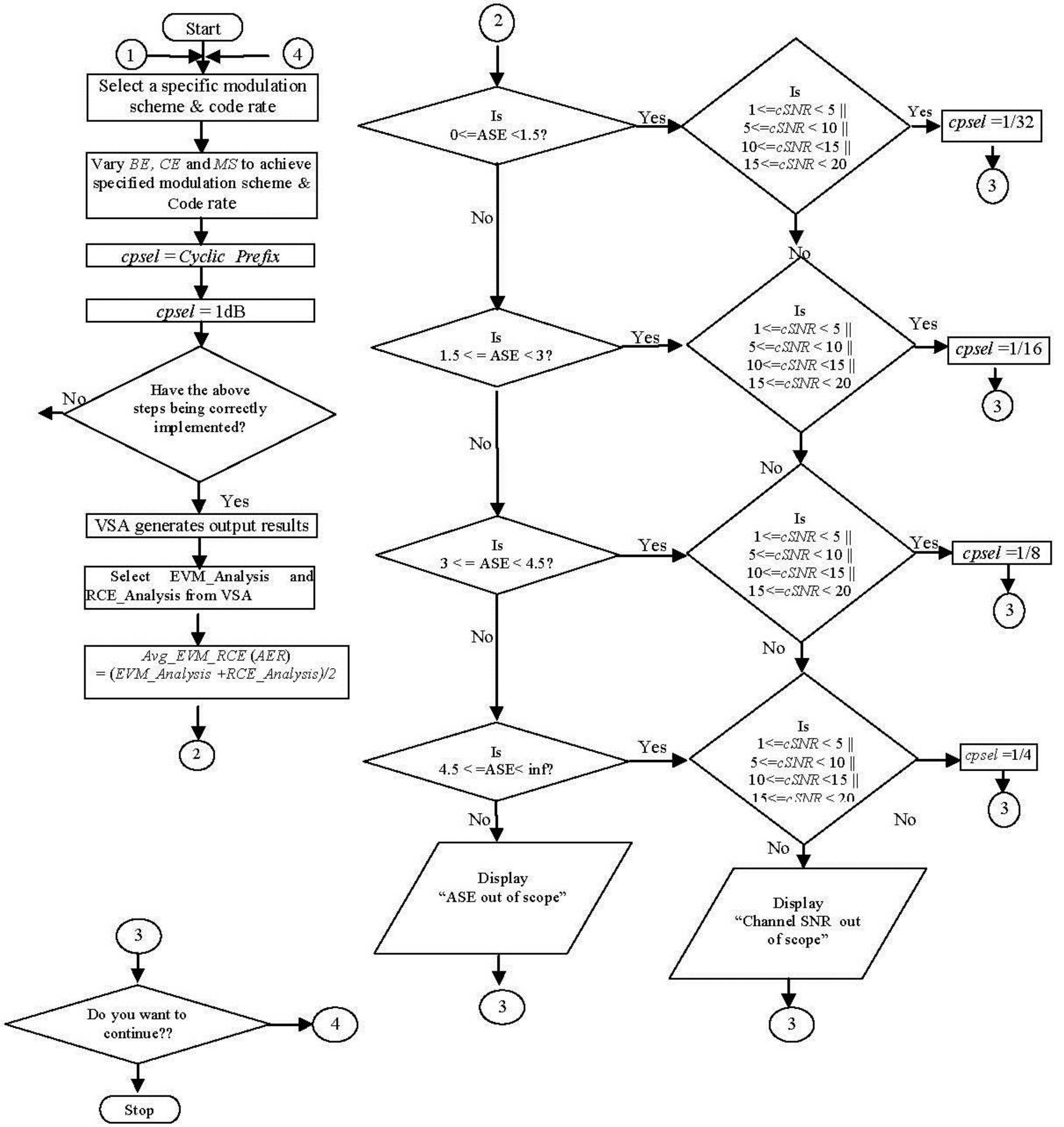

Figure 1. Flow chart for ESA Algorithm

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synchronization error is beyond certain threshold. As the current CP mitigates the effect of synchronization error to appreciable proportion, hopping between all available CPs is not at all a necessity. Hence ESA represents a unique strategy that helps in improving the overall signal strength of the transmitted signal by selecting smaller guard interval for longer duration of Channel SNR inherently decreasing loss in signal strength. It has already been proved in various literatures that a smaller guard interval always assists in improving SNR [4], [9]. Thus using ESA an improvement in SNR is observed.

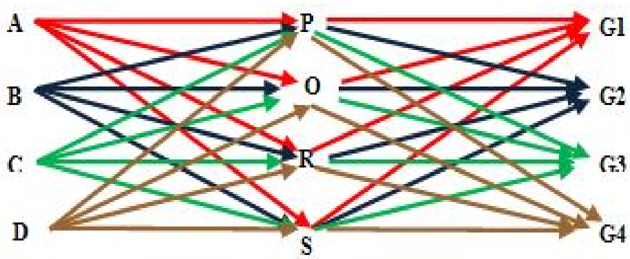

Figure 2. The one-to-one relationship between Average Error Offset, SNR and CP

IV. Simulation results and discussions

Application of ESA algorithm on a WiMAX based network provides conclusive evidence on the account of significant improvement of synchronization error offset. Moreover, ESA discards the hypothesis of using higher order modulation and coding schemes only when the distance between the Base Station (BS) and Mobile Subscriber (MS) is small and SNR is high. As for example, theoretical Downlink (DL) Throughput for a typical WiMAX network under 64-QAM modulation must be 10 Mbps at a distance of 560 m from the BS. Instead a more practical measurement records 3.86 Mbps DL Throughput at a distance of 524.6 m [18]. This drop in data rate is due to the inherent non ideal channel characteristics and different fading scenarios. Thus it is evident from Fig. 8 and Fig. 9 that application of ESA makes the error correction on the fly and reduces the loss in signal strength for 64-QAM (2/3 and 3/4). Moreover, less hopping between CPs and selection of smallest CP, keep SE to an appreciably high proportion for the entire duration of 1 dB-20 dB Channel SNR as given in Fig. 8. Even for BPSK(1/2), QPSK (3/4) and 16-QAM(1/2 and 3/4) ESA algorithm works to its potential by reducing loss of signal strength to significant proportions as depicted in Fig. 3 to Fig.7 respectively.

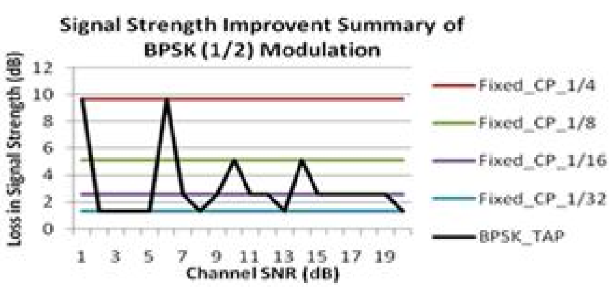

Figure 3. Signal Strength measurement of Fixed CP and ESA for BPSK(1/2)

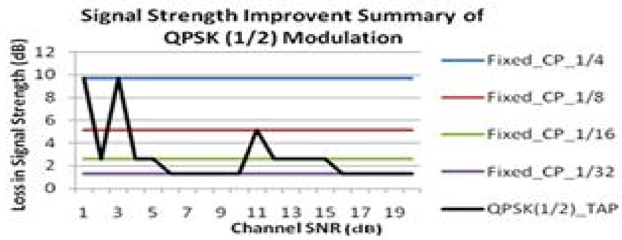

Figure 4. Signal Strength measurement of Fixed CP and ESA for QPSK (3/4)

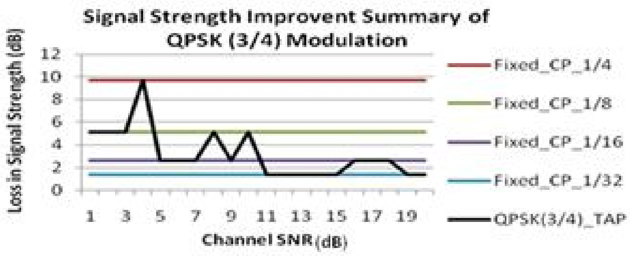

Figure 5. Signal Strength measurement of Fixed CP and ESA for QPSK (3/4)

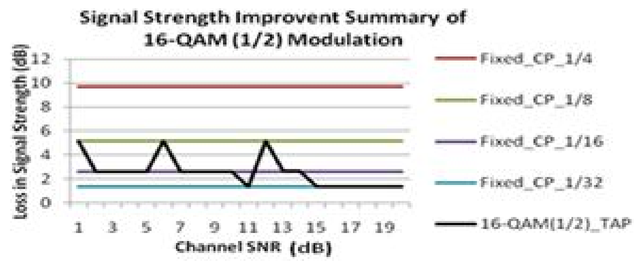

Figure 6. Signal Strength measurement of Fixed CP and ESA for 16 QAM (1/2)

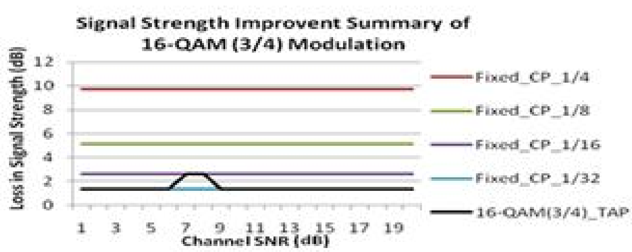

Figure 7. Signal Strength measurement of Fixed CP and ESA for 16-QAM(3/4)

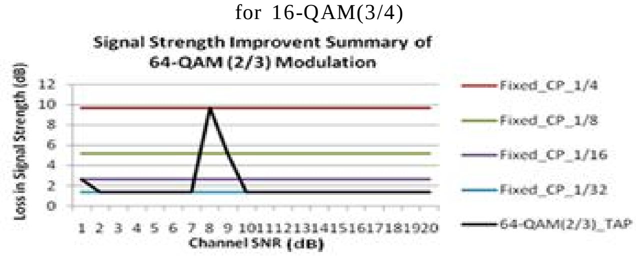

Figure 8. Signal Strength measurement of Fixed CP and ESA for 64-QAM(2/3)

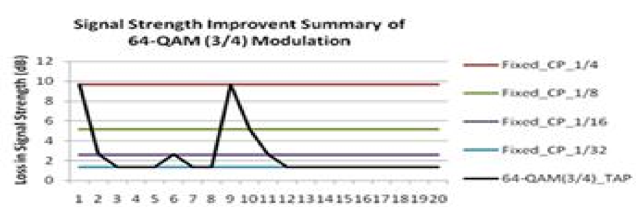

Figure 9. Signal Strength measurement of Fixed CP and ESA for 64-QAM (3/4)

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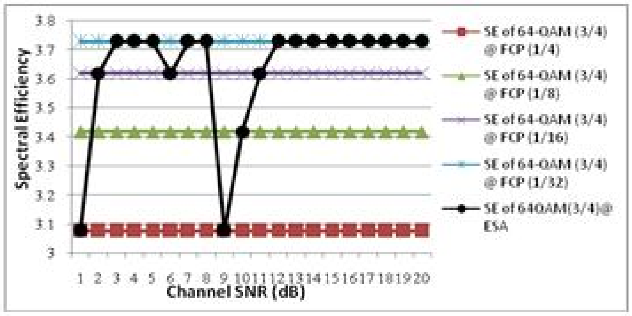

Figure 10. Spectrum Effeciency Summary for 64-QAM (3/4)

It is significant to observe that for 64-QAM (2/3 and 3/4), loss in signal strength remains almost negligible to 1.33 dB, for CP = 1/32 for Channel SNR ranging between 1dB to 20dB. This result is critical as it confirms that using a smaller CP; ASE gets reduced resulting in a better QoS. The selection of CP based on ESA results in maintaining a high RDR (selection of higher order modulation and coding at smaller Channel SNR) with an improved SE. As clearly depicted in Fig.10 the dynamic switching of SE guarantees a highly spectrally efficient system. The highest SE of 3.72 is reached even at most deteriorating channel condition, thus confirming the effectiveness of ESA.

V. Conclusion

Considering the existing ACP and MACP algorithms, an efficient unique ESA technique has been proposed in this paper. ESA not only improves RDR, but also inherently maintains a high SE under degrading channel condition for a typical WiMAX network. Additionally application of ESA results in much reduced signal degradation, than existing FCP WiMAX based scenario. Thus it also assures that higher order modulation scheme can merrily be accepted for data transmission at distances far away from BS. Specifically using ESA, a confirmation on using 64-QAM modulation and coding scheme at smaller Channel SNR has also been established.

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